Open Astron. 2017; 26: 214–218 DE GRUYTER OPEN

Research Article

Conor M. Byrne*, C. Simon Jeffery, Christopher A. Tout, and Haili Hu

Diffusion in hot subdwarf progenitors from the common envelope channel

https://doi.org/10.1515/astro-2017-0440
Received Sep 29, 2017; accepted Nov 11, 2017

Abstract: Diffusion of elements in the atmosphere of a star can drastically affect its surface composition, sometimes leading to unusual mixtures. These chemically peculiar stars can be identified from the presence of unusual lines in their spectra. Some hot subdwarf stars show extraordinary abundances of elements such as lead, zirconium and strontium, while the abundance of helium ranges from practically zero to almost 100 percent across the hot subdwarf population. A sequence of extreme horizontal branch star models was generated by producing a number of post-common envelope objects from red giants. The evolution of these subdwarf progenitors was computed with the MESA stellar evolution code from immediately after envelope ejection right up to the ignition of helium in the core. Envelope abundances were calculated at the zero age horizontal branch for models both with and without the presence of diffusion. A small number of simulations also looked at the effects on radiative levitation of these abundances, to test how well diffusion physics is able to reproduce observational data.

Keywords: atomic processes, stars: evolution, stars: subdwarfs

1 Introduction

Hot subdwarf stars are low mass, core-helium burning stars which have a fascinating evolutionary history. The most widely accepted theories point to the necessity of a binary interaction in order to form (Han et al. 2002, 2003). This interaction can take the form of a merger of two low mass helium white dwarfs, stable Roche lobe overflow from a red giant branch (RGB) star to a low mass companion or unstable mass transfer from a red giant to a companion, leading to the formation and subsequent ejection of a common envelope.

The presence of pulsations in some hot subdwarfs enables the probing of their interiors via asteroseismology. Observational studies have shown that helium surface abundances in hot subdwarfs can vary from almost 0 to 100 per cent. Other elements have also been found to have peculiar abundances, with particular examples showing elements such as lead and zirconium in quantities up to 10 000 times greater than that of the Sun (Naslim et al. 2011; Jeffery et al. 2017). The abundance of iron group elements in these stars is also quite high, typically exceeding the solar value by a large multiple (apart from iron). This diverse population of stars, contained in a mixture of binary and single star systems, along with their unusual evolution makes them an interesting tool for testing stellar evolution.

1.1 Abundance Anomalies and Atomic Diffusion

The origin of these exotic abundance anomalies is unclear, however it has been shown that the action of radiative levitation in the envelopes of hot subdwarfs causes the accumulation of iron and nickel necessary to drive the pulsations via the κ-mechanism (Charpinet et al. 1997).

Atomic diffusion is a general term referring to the processes of concentration diffusion, thermal diffusion, gravitational settling and radiative levitation. Concentration and thermal diffusion are driven by abundance and pressure gradients respectively. Gravitational settling is a result of the inward gravitational force acting differently on

Corresponding Author: Conor M. Byrne: Armagh Observatory & Planetarium, College Hill, Armagh, BT61 9DG, Northern Ireland; School of Physics, Trinity College Dublin, College Green, Dublin 2, Ireland; Email: cmb@arm.ac.uk
C. Simon Jeffery: Armagh Observatory & Planetarium, College Hill, Armagh, BT61 9DG, Northern Ireland; School of Physics, Trinity College Dublin, College Green, Dublin 2, Ireland
Christopher A. Tout: Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom
Haili Hu: Earth Science Group, SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

different atoms, with heavier atoms sinking faster and, conversely, the lightest atoms rising.

Radiative levitation arises due to the outward radiation pressure acting on different atoms. Each of these atoms has a different atomic structure and will absorb different amounts of radiation in the interior. In general, metals such as iron and nickel have a vast number of transition lines and will thus absorb more radiation than lighter elements, allowing them to remain supported in the atmosphere.

Here we present results from a self-consistent study of the effects of atomic diffusion (with and without radiative levitation) on the envelope composition of hot subdwarf progenitors that have come from the common-envelope ejection channel of evolution during the transition from the red giant branch to the zero-age horizontal branch. A more complete presentation of the results has been submitted for publication elsewhere (Byrne et al. 2017).

2 Computational Methods

The Modules for Experiments in Stellar Astrophysics (MESA) 1-dimensional stellar evolution code (Paxton et al. 2011, 2013, 2015) was used for these simulations. Starting with a 1 $M_\odot$ main-sequence star, evolution was followed to the red-giant branch. At various points close to the tip of the giant branch, a common-envelope ejection event was simulated by introducing a sudden large mass loss rate ($10^{-3}\,M_\odot yr^{-1}$) until only a small hydrogen envelope of $6 \times 10^{-3}\,M_\odot$ remained.

Evolution was followed during the transition from the red-giant branch (RGB), through the off-centre helium flashes up to the point of core helium ignition. Three sets of models were produced, referred to as 'basic' (no diffusion), 'standard' (diffusion without radiative levitation) and 'complete' (diffusion with radiative levitation) models. It is important to note that other processes such as mass loss and turbulent mixing, which could modify the envelope composition, were not considered in these simulations.

3 Results

The first result is that the timing of the common-envelope ejection plays an important role in determining the timing of the first helium flash, which affects the final structure of the subdwarf when it reaches the horizontal branch. The different scenarios identified agree quite well with the 'late hot-flasher' scenario as discussed in Brown et al. (2001). The models starting further from the RGB tip (thus having smaller core mass) consume some of their remaining envelope before the core becomes sufficiently large to ignite. This can happen shortly after moving off the RGB (a 'canonical' star) or while on the white dwarf cooling track (a 'flash-mixed' star). The canonical models undergo a helium flash, and the convection zone associated with the flash is unable to penetrate the entire hydrogen envelope. In the case of the flash-mixed stars, the strong convective zone produced by the flash is able to penetrate the thin hydrogen envelope which is then consumed in the hot interior of the star. This leaves the star with a helium-rich surface upon reaching the horizontal branch. It should be noted that envelope mass fractions reported here refer to the outer $10^{-8}\,M_\odot$ of the envelope, rather than the observable surface.

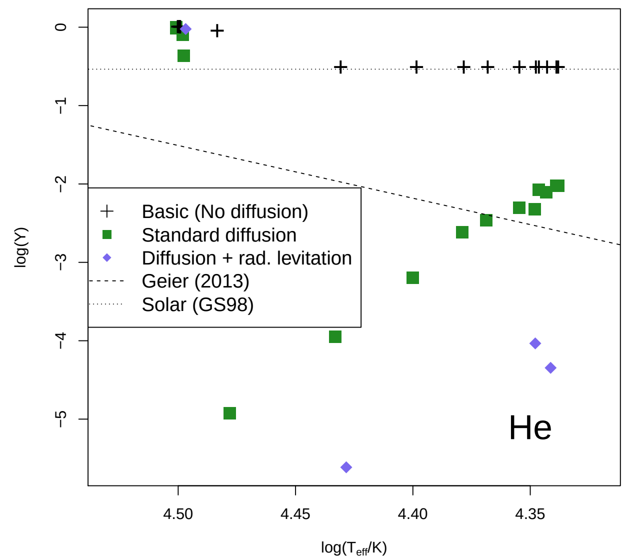

Figure 1. Surface helium mass fraction as a function of effective temperature for zero-age horizontal branch models. The black squares indicate models where no diffusion was included. The green squares show models where standard diffusion was included, while the blue diamonds represent models where diffusion and radiative levitation were included. The dotted and dashed lines represent the solar surface values and average sdB values from Geier (2013) respectively.

3.1 Helium abundances

A plot of the envelope helium mass fractions for the zero-age horizontal branch models is shown in Figure 1. With the absence of diffusion, the canonical models show no change in surface helium abundance, while the flash-mixed models reach the horizontal branch with helium-dominated atmospheres. The inclusion of diffusion sees the helium sink out of the outer layers of the canonical models. The abundances decrease for higher effective temperatures, which is a reasonable result since the hotter models also have a higher surface gravity, hence gravitational settling will be stronger. Including radiative levitation shows a similar result, with surface helium abundances being even lower for comparable models.

3.2 Diffusion of other elements

The diffusion of elements other than helium was also calculated. The elements chosen were C, N, O, Ne, Mg, Ar, Cr, Fe and Ni, as representative elements of interest for hot subdwarf stars. These were also chosen due to the availability of monochromatic opacity data from the Opacity project (Opacity Project Team 1995, 1997), enabling the calculation of radiative accelerations. The results for these elements are presented in Figure 2.

3.2.1 No diffusion

Without diffusion included, most models maintain the same surface composition as the RGB envelope, since there is no process present to alter it. Models which begun with a smaller core mass consume some of their remaining post-ejection envelope prior to helium ignition, thus ending up with a smaller envelope and higher effective temperatures, but the composition is unchanged. The flash-mixed models arrive at the zero-age horizontal branch with helium dominated atmospheres. Most other elements appear unchanged. Only C, N, O and Ne are altered due to the material being involved in the CNO process during the flash mixing.

3.2.2 Standard diffusion

With standard diffusion included, the action of gravitational settling serves to deplete the outer layers of heavier elements. In the flash-mixed models, the mass fractions increase in line with the depletion of hydrogen from the envelope as they now make up a larger portion of the mass. As with helium, a downward trend with increasing temperature (and gravity) is seen for these elements

3.2.3 Diffusion with radiative levitation

With the inclusion of radiative levitation, the picture is notably altered. In this case, lighter elements such as C, N, O Ne and Mg are depleted, while the heavier elements (Ar, Cr, Fe and Ni) are all enhanced relative to their initial envelope abundances. This is to be expected as iron group elements have a complex atomic spectrum, leading to absorption of a large amount of radiation, leaving them suspended in the outer layers of the star, while lighter, less opaque elements sink. The envelope compositions of the models are compared to the surface abundances of Geier (2013), indicated by the dashed lines in Figure 2. While these show a qualitative similarity (near-solar or super-solar abundances of heavy elements, depleted light elements), it can be seen that the changes to envelope abundances in the models are too extreme relative to the observations of surface abundances.

This suggests the presence of an additional mixing process to partially inhibit the effects of radiative levitation. These could include mass loss and turbulent mixing, which have not been considered in these models. It is also worth noting that MESA is an interior code, and thus an exact match between observed surface abundances and the theoretical envelope abundances is not expected without stellar atmosphere calculations, given the grey atmosphere assumptions used in the MESA simulations.

3.3 Comparison to other models

Enhancements of iron and nickel due to radiative levitation have also been found in other diffusion studies (Hu et al. 2011; Michaud et al. 2011, e.g.). These studies have used an equilibrium zero-age extreme horizontal branch model as a starting point for their simulations. The simulations presented here investigate the effects of diffusion during the transition from the RGB to the zero-age extreme horizontal branch after a common envelope phase. The results show that atomic diffusion plays a role in modifying the composition of hot subdwarf envelopes before they reach core helium ignition, implying that even very young hot subdwarfs should have modified surface abundances.

4 Summary & Future Work

By following the evolution of post-common envelope objects as they transition from the RGB to the horizontal branch, it was found that the effects of diffusion are al-

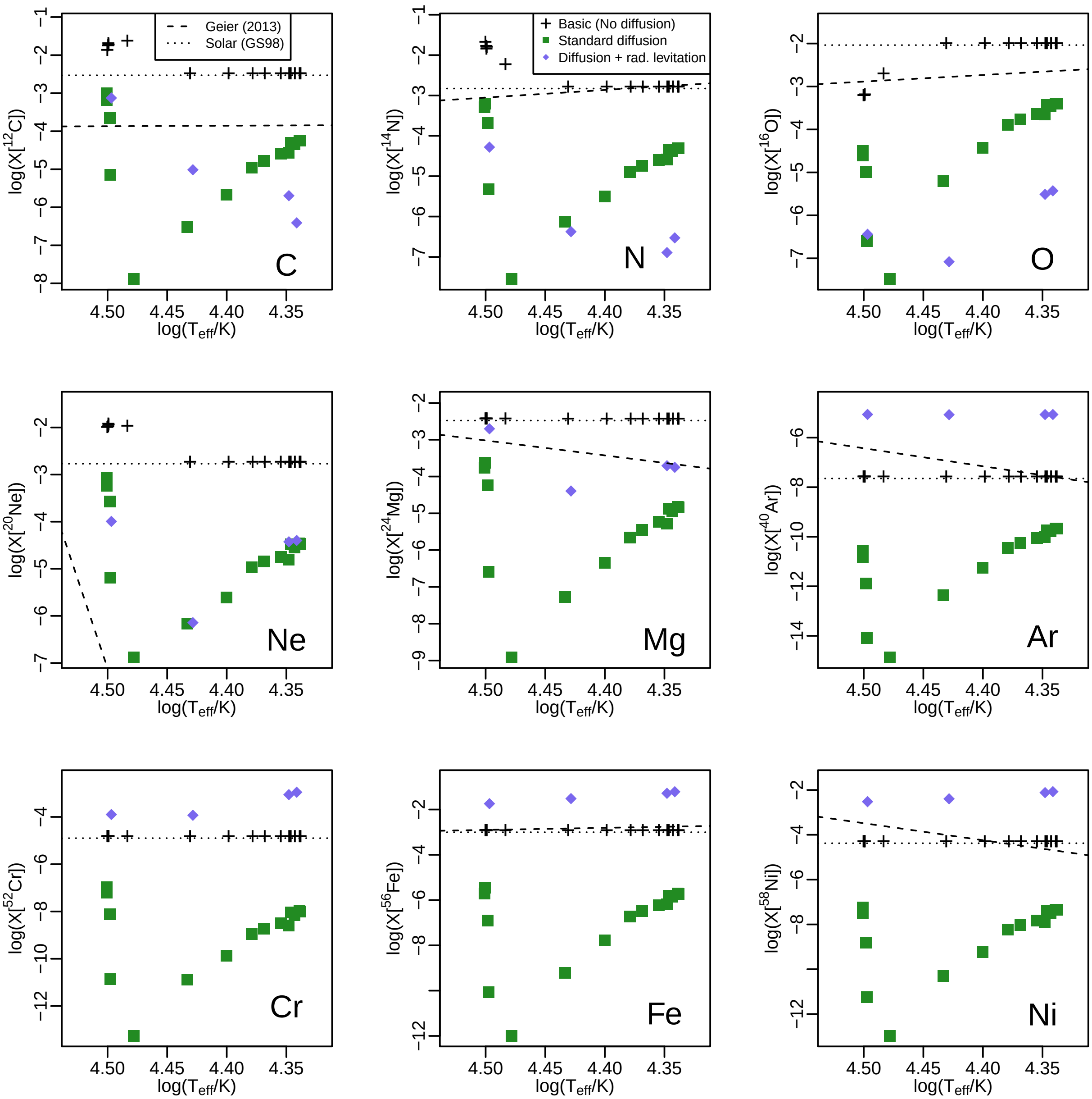

Figure 2. Envelope mass fractions as a function of effective temperature for zero-age horizontal branch models. The symbols and lines have the same meaning as in Figure 1.

ready significant by the time the star reaches the zero-age extreme horizontal branch.

The core mass at envelope ejection determines whether the star will flash as it leaves the RGB to give a canonical horizontal branch, or flash while on the white dwarf cooling track, giving a flash-mixed, helium-rich subdwarf. Smaller core masses typically lead to flash-mixed models. Radiative levitation leads to the enhancement of elements such as Cr and Fe in the envelope of these stars, while lighter elements such as C and N remain under-abundant. A more detailed analysis of these results will be published in Byrne et al. (2017).

In order to investigate the ability of radiative levitation to explain the origin of supersolar abundances of Pb and Zr in some extremely peculiar subdwarfs, detailed atomic data calculations are required. Analysis of the pulsation properties of these models during their transition from the red giant branch to the horizontal branch will be carried out, to compare with currently known pulsators and to evaluate the extent of the extreme horizontal branch instability strips.

References

Brown, T. M., Sweigart, A. V., Lanz, T., Landsman, W. B., Hubeny, I. 2001, ApJ, 562, 368–393.
Byrne, C. M., Jeffery, C. S., Tout, C. A., Hu, H. 2017, MNRAS, submitted
Charpinet, S., Fontaine, G., Brassard, P., Chayer, P., Rogers, F. J., Iglesias, C. A. et al. 1997, ApJ, 483, L123-L126.
Geier, S. 2013, A&A, 549, A110-A121.
Han, Z., Podsiadlowski, P., Maxted, P. F. L., Marsh, T. R., Ivanova, N. 2002, MNRAS, 336, 449–466.
Han, Z., Podsiadlowski, P., Maxted, P. F. L., Marsh, T. R. 2003, MNRAS, 341, 669–691.
Hu H., Tout C. A., Glebbeek E., Dupret M.-A., 2011, MNRAS, 418, 195-205
Jeffery C. S., et al., 2017, MNRAS, 465, 3101-3124
Michaud G., Richer J., Richard O., 2011, A&A, 529, A60-A80
Naslim N., Jeffery C. S., Behara N. T., Hibbert A., 2011, MNRAS, 412, 363-370
Opacity Project Team 1995, The Opacity Project, Vol. 1, Institute of Physics
Opacity Project Team 1997, The Opacity Project, Vol. 2, Institute of Physics
Paxton, B., Bildsten, L., Dotter, A., Herwig, F., Lesaffre, P., Timmes, F. 2011, ApJS, 192, 3.
Paxton, B., Cantiello, M., Arras, P., Bildsten, L., Brown, E. F., Dotter, A. et al., 2013, ApJS, 208, 4.
Paxton, B., Marchant, P., Schwab, J., Bauer, E. B., Bildsten, L., Cantiello, M. et al., 2015, ApJS, 220, 15.